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DESIGN OF A FIBER OPTIC DATA LINK FOR THE GROUND LAUNCHED CRUIS--ETC(U)
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DESIGN OF A FIBER OPTIC DATA LINK FOR THE GROUND LAUNCHED CRUISE MISSILE

CR Hansen
TP Fitzgerald
RA Greenwell

30 May 1980

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Prepared for:
Chief of Naval Material Joint Cruise Missile Program Office
JCM-M-60

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This report examines the feasibility of using fiber optic data links to connect the operating units of the Ground Launched Cruise Missile Weapons Control System. The conclusion is reached that the necessary technology to implement such a design is either presently available or will become available by mid-1980.

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OBJECTIVE

To provide, on a link basis, an independent approach to the design of a Fiber Optic Data Link (FODL) for the Ground Launched Cruise Missile (GLCM).

RESULTS

From a conventional fiber optics standpoint, design of a FODL for the GLCM is a relatively simple task. The severe environmental constraints, however, including the necessity to withstand a specified nuclear event, present a potential FODL design problem.

The electrooptic and electronic components necessary to implement the GLCM FODL are well within current state-of-the-art technology. Likewise, present radiation hardening techniques for electronic systems are more than adequate to provide protection for the FODL electronics. Presently, no cable that fully meets the FODL environmental requirements has been demonstrated. Likewise, no connector is available that fully satisfies the GLCM FODL requirements. Work is going forward in both areas, however, and suitable cables and connectors (fully tested to the GLCM requirements) are expected to be available within the next 6 months.

RECOMMENDATIONS

1. Closely monitor the progress of cable and connector development and testing on a worldwide basis.

2. Procure, for testing specifically oriented to GLCM requirements, candidate cables and connectors.

CONTENTS

INTRODUCTION

The subject of this report is the fiber optic data link (FODL) which, in conjunction with the signal multiplexing set (SMS), forms the signal transfer unit (STU) portion of the signal transfer system (STS) used in the cruise missile weapons control system (WCS). Specifically, this report will be tailored to application of the FODL to the ground launched cruise missile (GLCM) WCS.

Figure 1 shows a typical GLCM configuration. Note that two launch control centers (LCCs) and four transporter erector launchers (TELs) are included.

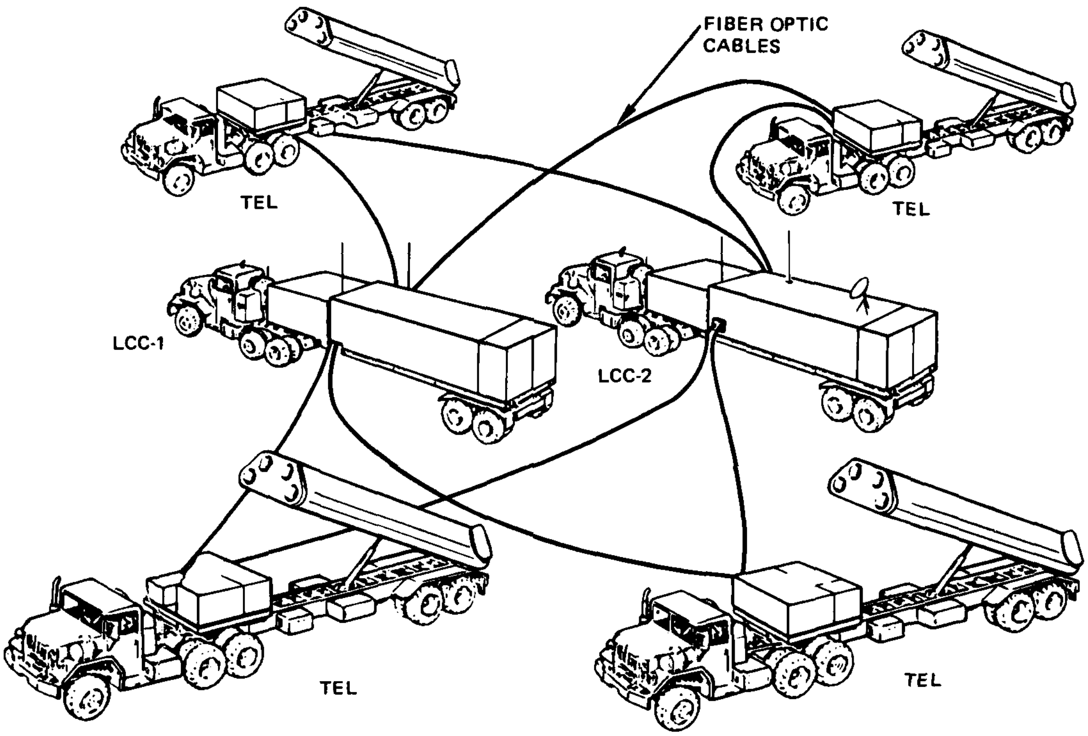

Figure 1. Typical ground launched cruise missile configuration.

Figure 2 is a functional block diagram showing the interconnect of the six STUs that form an STS.

Figure 3 is a functional block diagram of a single FODL showing its relationship to the STU, hence the STS.

Considering link length (300 m) and data rate (1 Mb/s) only, the design of the FODL would seem to be a trivial task, given the present state of fiber optic technology. Even considering the severe temperature (−54°C to +65°C) and mechanical constraints, components are readily available to implement a satisfactory low cost electrooptic design. The difficulty then, lies not in the electrical or mechanical aspects of the design, but in hardening the design to withstand nuclear radiation. Attendant with nuclear radiation, severe dynamic range constraints (not present in conventional designs) exert themselves. A separate section of this report will be devoted to examination of the radiation problem,

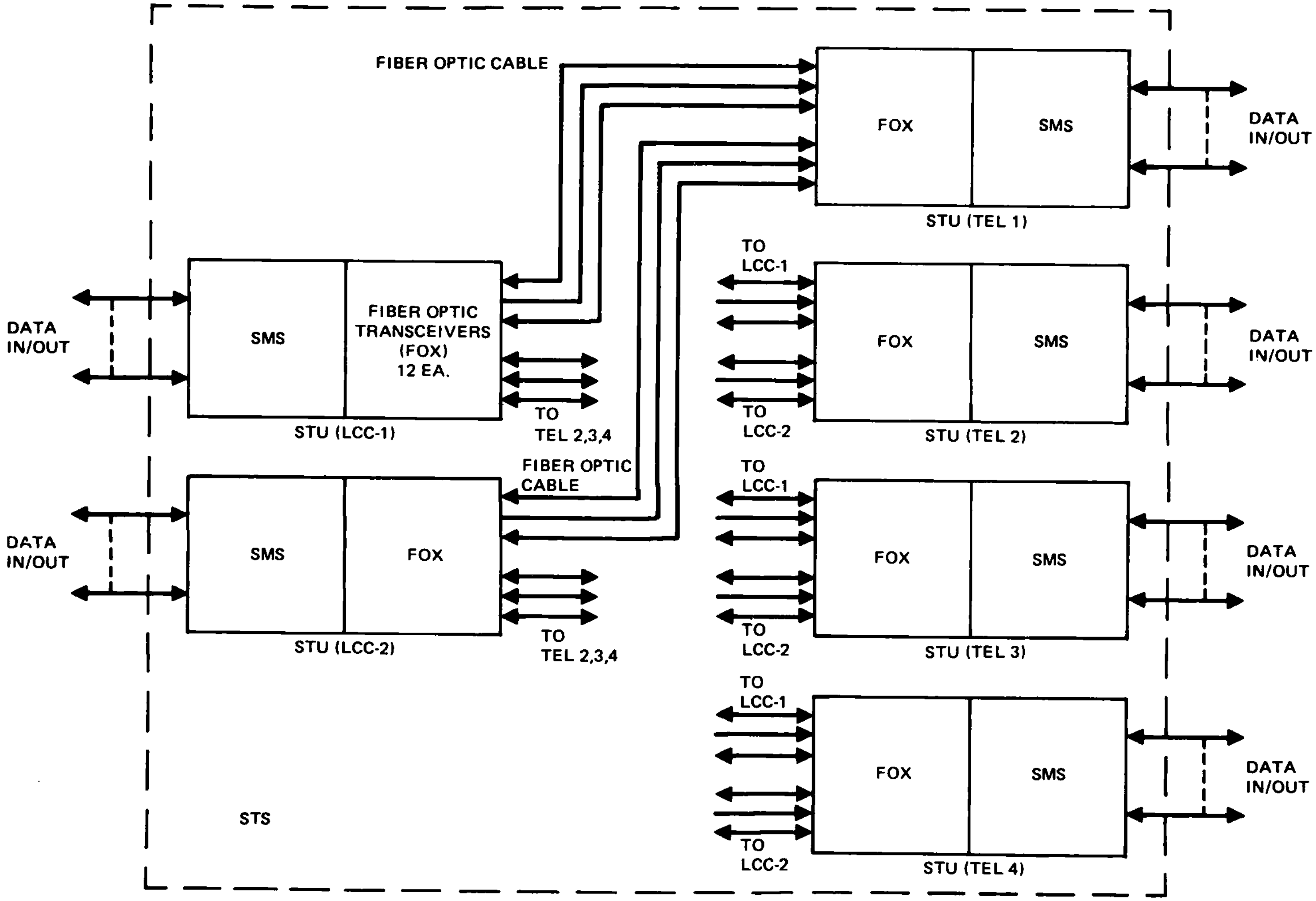

Figure 2. Signal transfer system functional block diagram.

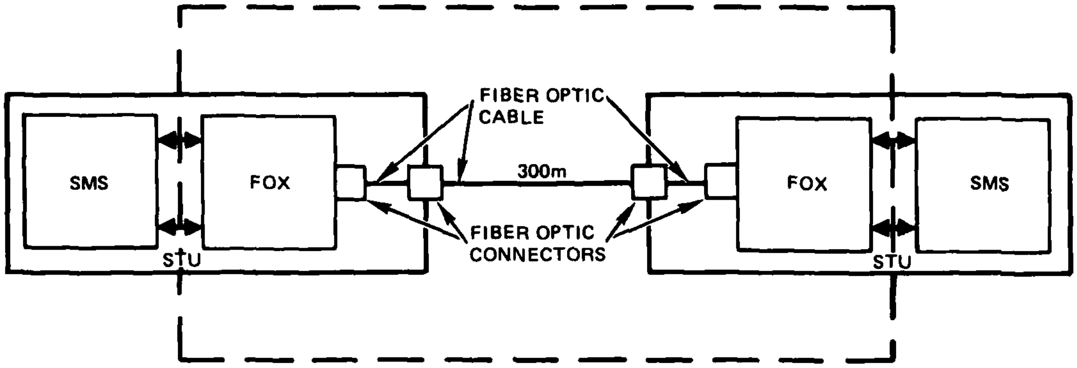

Figure 3. Fiber optic data link functional block diagram.

and various aspects thereof will be touched upon throughout the report. The effect of nuclear radiation upon optical fibers will be examined in the section on cables, and the ensuing dynamic range problem will be discussed in detail in the link analysis/budget section. Sources, detectors, and connectors will be studied within the same framework and, finally, a section will be devoted to built-in test (BIT).

COMPONENTS

CABLES

Problems associated with nuclear environmental effects on fiber optics can be categorized into two primary areas: Transient radiation effects on the optical fibers and nuclear thermal effects on the cables. In addition, many fibers which exhibit promising resistance to radiation effects have various mechanical or low temperature problems which tend to preclude their use in the GLCM FODL. In the following paragraphs we will discuss these problems, first as they relate to fibers, then as they relate to the jacketed cable.

FIBERS

Two transient effects in fibers can be produced by ionization. One is luminescence, which could produce temporary detector saturation. The second and most important effect, because of its slow decay time, is an increase in fiber attenuation. This initial increase in attenuation can produce a transient loss of signal in a link, the duration of which is dependent upon both the level of exposure and the margin of the link. Steady state transient effects in fibers are much the same as prompt pulse effects. Steady state effects, however, do not occur at the same dose rate as prompt transient pulses, since recovery is taking place at the same time as generation. To predict the level of attenuation produced by a steady state environment, it is necessary to combine the production rate and the recovery rate, keeping track of how much time has elapsed since any exposure increment.

In order to determine the effects of radiation on various types of fiber, extensive testing programs have been undertaken by the Naval Research Laboratory, Harry Diamond

Laboratories, Rome Air Development Center and others. Results have been mixed; however, some are consistent and worthy of note here. These results are as follows:

1. The most radiation resistant optical fibers measured to date have been fibers which use high purity synthetic silicas as core materials.

2. Germanium doped pure silica core fibers exhibit only minimal pulsed or steady state effects at room temperature; however, recovery from prompt ionizing doses at high temperatures (60°C) is problematical, and potential low temperature (defined throughout as –40°C) problems have not been evaluated extensively.

3. In a steady state ionizing environment, the presence of boron and/or phosphorus as co–dopants with germanium increases the attenuation significantly at low temperature.

4. Fluorine as a dopant enhances the radiation resistance of silica at room temperature; low temperature data are not available.

5. Boron as a dopant decreases the radiation resistance of silica substantially, especially at low temperature, and slows recovery time following irradiation.

6. Polymer clad silica (PCS) fibers have proved to be the most radiation resistant fibers at room temperature. Unfortunately, they generally exhibit high intrinsic losses at low temperatures (two exceptions are the Maxlite MSC-200 ARH-LT and the Quartz Products QSF A-200 special, which are designed to withstand low temperatures).

Based on the above, the best commercially available fibers on the market today are the Maxlite MSC-200 ARH-LT, a large core (200 μm) PCS fiber designed to withstand low temperatures; the Quartz Products QSF A-200 special, another large core PCS fiber designed to withstand low temperature; the ITT T-323 and Valtec PC-10, both large core PCS fibers; the Corning SDF fiber, a germanium doped pure glass-glass fiber with a 100 μm core; and the Gallite 5020 Special, a germanium-boron doped 125 μm core glass-glass fiber (low temperature test data are not yet available on this fiber).

If radiation resistance were the sole determining factor in selecting a fiber, the Maxlite and Quartz products fibers would seem to be ideal. But, as previously mentioned, PCS fibers also exhibit various mechanical problems which tend to make them less desirable. Two of the more serious problems are:

1. The silica core moves within the plastic cladding during temperature cycling. This leads to protrusion of the glass core from the end of the cladding, resulting in potential destruction of the fiber end.

2. PCS fibers are difficult to attach to connector ferrules with epoxy. The result is a weakened ferrule-fiber connection.

Unless these problems can be solved, PCS fibers would seem to be an undesirable choice for the GLCM FODL since it will be deployed under potentially rigorous environmental and handling conditions.*

*Quartz and Silice claim to have a low temperature resin which, when used as the fiber cladding, eliminates the problem of fiber protrusion.

Raychem (Maxlite) claims to have developed a termination technique which eliminates ferrule-fiber connection problems.

When data become available to support these claims, PCS fibers will be re-evaluated.

The choice for a fiber then, narrows to the two glass-glass fibers previously mentioned, the Corning SDF and the Gallite 5020 special, or to a fluorosilicate clad pure silica core fiber being developed by ITT under contract to NOSC. Complete test data are not presently available on any of these fibers, and the final choice must necessarily await said data.

CABLES

Nuclear testing of fiber optic cables has shown that many jacketing materials, polyurethanes, polyvinylchlorides (PVC) and fluorocarbons disintegrate at low thermal pulse levels. Polyurethane jacketed cables not containing flame retardants showed breaches in the jacketing at 27 cal/cm^2, PVC at 27 cal/cm^2, polyurethane with flame retardant at 65 cal/cm^2, and clear fluorocarbon at 65 cal/cm^2.

Materials with low absorption (white teflon and aluminum foil) effectively increased the survivability of cable to which they were applied. Teflon tubing survived at 174 cal/cm^2, with discoloration being the only apparent effect. Thus, white or clear teflon jackets over white teflon tape appear to be a viable thermal hardening technique for the GLCM FO cable.

CONNECTORS

A survey of connector manufacturers revealed five companies currently engaged in the development of multichannel fiber optic connectors designed to withstand tactical field use. Hughes Aircraft, ITT Cannon, Amphenol, Cinch, and Stratos (Swedish) have products which may be suitable for the GLCM FODL. The following list identifies the companies and pertinent information.

1. Hughes Aircraft part #11270295 is a six-channel hermaphroditic connector with an insertion loss of 1.4–1.7 dB. A spring loaded free floating contact alignment is used to achieve the low loss. Variations are directly attributable to tolerances of the fiber core diameters (125 μm). The fibers are crimped to the contact via a soft metal bushing. Disassembly is required for cleaning.

2. ITT Cannon part #TG532-6 is a six-channel hermaphroditic connector with an insertion loss of less than 2 dB. It uses a jeweled ferrule capable of accepting an 85–265 μm core fiber. Disassembly is required for cleaning.

3. Amphenol series 801 with a 901 strain relief provides an 8-channel polarized connector with an insertion loss of less than 2 dB. A spring loaded free floating contact alignment is used to achieve the low loss. The 125 μm or larger fiber core is epoxied to the #16 size contact. Disassembly is required for cleaning.

4. Cinch is under Army contract to develop a six-channel connector for tactical field use. The connector is a hermaphroditic design that uses a 4-rod V-groove alignment system. Loss is projected to be less than 1 dB in the production model. A special cleaning kit for field use is under development, as is a field termination kit.

5. AB Stratos of Sweden is reported to be developing a 4- or 6-channel connector with a 1.5 dB insertion loss. No distributor is currently available within the United States.

All manufacturers, with the exception of AB Stratos who was not directly contacted, claim their connectors will satisfy the environmental requirements imposed upon the GLCM FODL. The actual degree of in-house or independent government sponsored testing is unknown at this time.

The near term available connectors all offer no optics protection other than end caps when the cable is disconnected from the LCC/TEL. It is likely, therefore, that small particle contamination will occur during ordinary field usage, with the ensuing risk of fractures to the polished fiber ends. This contamination may not be obvious to a discerning visual inspection. Therefore, the cable deployment instructions must demand a cleaning procedure each time a connection is made. Suitable equipment (ie, rechargeable air gun, and/or propellant charged cleaning solution) should be supplied to afford the field user a quick and effortless cleansing method without substantially affecting the overall cable deployment time. Additionally, adequate instruction and tooling are needed should the connector suffer gross contamination, ie, water, snow, or mud.

SOURCES

Candidate sources for use with the FODL include laser diodes (LDs) and light emitting diodes (LEDs). In general, source characteristics of interest include power output (as a function of time and temperature), spectral width and wavelength, size, coupling efficiency, lifetime, speed, and cost. For the FODL, radiation effects must also be considered. Both source types have distinct advantages and disadvantages; these will be discussed in the following paragraphs.

LASER DIODES

Laser diodes offer high power output and narrow spectral widths (1 nm) and emission angles (5°). Due to the high power output and narrow emission angle, LDs couple, typically, 10 to 15 dB more power into a fiber than do LEDs. The narrow spectral width causes negligible material dispersion in a fiber, thus LDs are best suited to long haul (> 1 km) high data rate (>50 Mb/s) applications. While speed is not a concern in the FODL application, the LD's high output power capability would seem to make it an attractive source for use in a system (such as the FODL) which has to concern itself with greatly increased fiber attenuation under certain conditions (nuclear event – low temperature).

Laser diodes, however, suffer from operational deficiencies that tend to make them much less attractive than they appear on the surface.

First, they are so temperature sensitive that small (5–10°C) changes in temperature can cause their lasing threshold to change significantly. Since the LD must be operated in a restricted current range just above its lasing threshold, small changes in temperature can cause large changes in the lasing thresholds of the diodes and hence their output power. In the worst case (at high temperature) the threshold of the diodes may increase sufficiently to prevent lasing. To allow for temperature effects, relatively sophisticated compensation circuits are necessary whenever LDs are to be used at other than a fixed temperature. This adds complexity and increases power consumption, while decreasing the reliability of the design.

Second, since LD power output curves are so steep, some form of optical feedback is necessary to maintain a constant power output over time and temperature. This adds more complexity to the design and further decreases reliability.

Third, LDs exhibit a tendency toward vibrational and shock induced instability. This tendency means exceptional care must be taken in the mechanical packaging of an LD transmitter, and results in additional volume, weight, and cost.

Fourth, although 50,000-hour lifetimes have been claimed for some LDs, evidence to support such claims is sketchy, and LD based designs have historically proved to be less reliable than LED based designs.

For these reasons, LDs should be used only where LEDs are inadequate for the task.

LIGHT EMITTING DIODES

Light emitting diodes offer (compared to LDs) greater temperature and temporal stability, longer lifetimes, and greater reliability. LEDs are presently available that exhibit less than 1 dB change in power output over the required FODL temperature range (–54°C to +65°C). This eliminates the need for temperature compensation schemes similar to those needed for LD operation. Temporally, the half life of commercially available LEDs is in the 50,000-hour range, and since LED power output curves are relatively gradual, optical feedback is not required to maintain constant power output.

LEDs, however, offer lower output power than LDs, have broader spectral widths (35 nm) and wider emission angles (20°). The wide LED spectral width results in increased material dispersion, thus limiting the bandwidth of LED based systems (exclusive of detectors) to about one-tenth that of LD based systems. Due to lower output power levels and wider emission angles, LED coupling efficiency is low and, as noted above, LEDs couple 10 to 15 dB less power into a given fiber than do LDs.

For the FODL, bandwidth (hence dispersion) is not a problem since the link length is only 300 m and the required data rate 1.0 Mb/s Manchester. Power output, however, could prove to be a problem since the FODL must withstand appreciable darkening of the fibers due to nuclear radiation, and still remain operational.

Selection of a source type is dependent, therefore, upon the characteristics of the chosen fiber, and also upon the type of detector selected. Because of ease of implementation, LED based designs are generally indicated for all systems where power and bandwidth considerations permit.

DETECTORS

Candidate detectors for use with the FODL include avalanche photodiodes (APDs) and PIN photodiodes (PINs). In general, detector characteristics of interest include sensitivity, dynamic range, spectral response, stability as a function of time and temperature, speed and cost. For the FODL, radiation effects must also be considered. Both detector types have distinct advantages and disadvantages; these will be discussed in the following paragraphs.

AVALANCHE PHOTODIODES

Avalanche photodiodes combine optical signal detection with internal amplification of photocurrent. Because of their current gain, APDs have a much greater (order of magnitude) sensitivity than PINs. However, due to the avalanche gain of the diodes (typically 100), dynamic range in a given receiver is less for an APD than for a PIN. Response times of APDs are typically <5 ns, and of the same order as those for PINs. Lifetimes are on the order of 50,000 hours.

APDs, however, suffer from many of the same operational problems that make LDs unattractive for use under severe environmental conditions. As is the case with LDs, APDs are extremely temperature sensitive (gain changes approximately 2% per °C), thus sophisticated temperature compensation circuits must also be used with APDs. With an APD, however, the problem is further complicated by the fact that APD gain is a direct function of the reverse bias (typically 250–350 V) applied to it. The impact of this biasing requirement on receiver design is twofold. First, a variable high voltage power supply must be provided internal to the receiver; second, the temperature compensation design must be used in conjunction with an overall automatic gain control (AGC) scheme that varies the APD bias as a function of temperature and optical signal strength. The overall effect of this arrangement is a drastic increase in receiver complexity, and an equally drastic decrease in receiver reliability (as compared to a PIN receiver).

In the case of the FODL, an additional constraint must be placed upon any APD based receiver design. Since the system dynamic range requirements are large (due to radiation darkening of the fibers), during prenuclear operation tens of microwatts of power will be incident upon the detector. If the APD is not protected, this incident power will be enough to overload and possibly destroy it. Protection for the APD may be (in its simplest form) a current limiting resistor in the bias line. In the case of the FODL, however, the environmental constraints would tend to dictate a more complex scheme tied in with the temperature compensation circuitry.

PIN PHOTODIODES

PIN Photodiodes also require reverse biasing to operate properly. However, contrary to APD requirements, high voltage biasing (50–100 V) is required only in high speed (tr <5 ns) applications. For the FODL, bandwidth requirements are minimal, therefore low voltage biasing (5–10 V) is adequate. PINs exhibit excellent temperature and temporal stability; indeed, no special temperature compensation is required for a PIN operated within the FODL temperature range. While an AGC scheme will be required to prevent receiver saturation and the resultant pulse distortion, the design will be much simpler than that for an APD, since the diode itself will not be part of the loop. Additionally, PINs are capable of handling milliwatts of power without damage; therefore no special consideration need be given to diode protection.

PINs exhibit an order of magnitude less sensitivity than APDs, but (for a given receiver) they provide an order of magnitude greater dynamic range.

As with the LD – LED tradeoff, the choice of an APD or PIN for use with the FODL is dependent upon the other system components. In the following section the necessary tradeoffs will be made, and the FODL components identified.

LINK ANALYSIS

CABLE/CONNECTORS

As is the case with most fiber optic transmission systems, the cable selected for the GLCM FODL will be the driving force behind component selection.

In general, the cable selected will exhibit parameters consistent with use of the most reliable and lowest cost sources and detectors. In order of preference these combinations are: LED-PIN, LED-APD, LD-PIN and LD-APD. For the GLCM FODL, given its severe environmental constraints, a LED-PIN combination is highly desirable. Because of the environmental constraints placed upon the GLCM FODL, specifically the nuclear and temperature restrictions, selection of an appropriate cable will be more difficult than normal. Several cables (Galite 5020 special, Corning SDF) do exist, exhibit promising qualities, and may be suitable for GLCM. Candidate fibers are all in the 10 dB/km range (70 dB/km postnuclear event); however numerical apertures (NAs) vary from 0.25 to 0.4, and core diameters from 125 μm to 200 μm. A 125 μm core, 0.25 NA fiber, will be assumed for purposes of this analysis. Additionally, worst case conditions (-54°C and +65°C postnuclear event) will be assumed.

The assumed fiber, then, will exhibit the following properties:

1. Prenuclear event attenuation $\leqslant$ 17 dB/km (-54°C) and $\leqslant$ 10 dB/km (+65°C) at 820 nm
2. Postnuclear event attenuation $\leqslant$ 77 dB/km (-54°C) and $\leqslant$ 70 dB/km (+65°C) at 820 nm
3. Numerical aperture $\geqslant$ 0.25
4. Core diameter = 125 μm
5. Bandwidth $\geqslant$ 25 MHz-km

For a 300 m FODL, the total cable attenuation will be 5.1 dB and 3 dB prenuclear event, and 23.1 dB and 21 dB postnuclear event at -54°C and +65°C respectively. Worst-case connector losses of 2.5 dB per connector will add an additional 10 dB link loss to the FODL, giving total losses of 15.1, 13, 33.1, and 31 dB, respectively.

DETECTOR

An accurate estimate of the power required at the receiver in order to achieve the specified bit error rate of 1×10^{-9} is needed.

If the receiver output (prior to data reconstruction) is approximated by signal plus additive Gaussian noise, bit error rate (BER) is related to signal-to-noise ratio (SNR) by the expression:

$$\mathrm{BER} = 1/2 \ \mathrm{erfc} \ \frac{1}{2\sqrt{2}} (I_s/I_n) \qquad (1)$$

where erfc is the error function complement, I_s is the peak signal current, and I_n is the rms noise current. For BER = 1×10^{-9}, the value of I_s/I_n is 12 (21.6 dB).

In an optical receiver using an APD as the detection element, the input noise current is composed of three primary components. These are summarized below:

$$I_q = \text{quantum noise} = (2q\ r\ P_s\ F\ B)^{1/2}\ G \quad (2)$$

$$I_d = \text{dark current noise} = (2q\ I_D\ F\ B)^{1/2}\ G \quad (3)$$

I_a = amplifier noise

where

P_s = peak optical signal power = I_s/r

r = photodiode responsivity (0.5 amps/watt)

q = charge on an electron (1.6×10^{-19} coulombs)

F = APD excess noise factor = $G^{0.4}$

B = noise bandwidth

G = APD gain

I_d = dark current of APD

Amplifier noise (I_a) is composed of shot noise due to input stage bias currents and thermal noise associated with the input load or feedback resistor. Obviously I_a is dependent upon the amplifier configuration used, but a conservative value for a 1.5 MHz noise bandwidth (1 MHz – single pole signal bandwidth) amplifier is 1 na.

APD dark current is a function of temperature, increasing by a factor of 2 for every 10°C rise in temperature. A typical value of I_d at 25°C is 0.1 na. At +65°C, this current has increased to 1.6 na; at –54°C it is negligible.

For purposes of calculation, the following typical APD characteristics will be assumed:

I_d = 1.6 na (65°C)

I_d = 0 (–54°C)

G = 100

F = $G^{0.4}$

r = 0.5

B = 1.5 MHz

Substituting these values into eq (2) and (3) gives:

$I_q = 1.2 \times 10^{-4} P_s^{1/2}$

$I_d = 7 \times 10^{-9}$a

$I_a = 1 \times 10^{-9}$a

Since the noise sources are uncorrelated, they add in an rms fashion, hence the SNR is given by:

$$I_s/I_n = r\,P_sG/(I_q^2 + I_d^2 + I_a^2)^{1/2} \tag{4}$$

Setting $I_s/I_n = 12$ and substituting into eq (4) yields

$$12 = 50\,P_s/[1.44 \times 10^{-8}P_s + 4.9 \times 10^{-17} + 1 \times 10^{-18}]^{1/2} \tag{5}$$

Solving eq (5) gives $P_s = 2.15$ nW at +65°C. A similar calculation results in $P_s = 0.84$ nW at -54°C.

In a PIN based receiver, preamplifier noise usually predominates over photodiode related dark current and quantum noise. As noted above, $I_a = 1$ na is a reasonable estimate for a low noise 1.5 MHz bandwidth amplifier. SNR for the PIN receiver is given by:

$$I_s/I_n = r\,P_s/I_a \tag{6}$$

Substituting and solving eq (6) for P_s yields

$$P_s = 12(1 \times 10^{-9})/0.5 \tag{7}$$

or $P_s = 24$ nW, a figure that will remain relatively constant throughout the entire temperature range.

To summarize, then, the power required at the receiver to achieve a SNR = 12 is:

$$\left.\begin{array}{l} P_s = 0.84 \text{ nW at } = 54°\text{C} \\ P_s = 2.15 \text{ nW at } 65°\text{C} \end{array}\right\} \text{APD}$$

$$P_s = 24 \text{ nW} \qquad \text{PIN}$$

SOURCE

Having identified the required detector power levels and associated cable/connector losses, we are now in a position to determine the type of source required for the GLCM FODL. At -54°C, peak power required by an APD receiver is 0.84 nW, and cable/connector losses are 33.1 dB. At +65°C the comparable figures are 2.15 nW and 31 dB. For a PIN receiver, the required power is 24 nW, while link losses are as noted above.

Taking the required receiver power and multiplying by the link losses, we arrive at the minimum coupled power (source to fiber) necessary for link operation. These power levels are 1.71, 2.7, 49 and 30 μW respectively; levels which are consistent with either LED-APD or LED-PIN operation, thus a LED–PIN link is indicated.

At least two LEDs (Spectronics SE3352, Laser Diode Labs LDT 245) appear to be ideally suited to the GLCM FODL. In contrast to most commercially available LEDs, which project a Lambertian output power profile, these devices use an integrated lensing system which effectively columnates the output profile into a 300 μm spot. The effect of this columnation is to make the power coupled into a fiber essentially independent of NA (for NA > 0.25), and dependent only upon fiber core diameter.

At a nominal 100 ma of drive current, these devices will couple approximately 170 μW into a 125 μm core fiber at 25°C. With a temperature coefficient of -0.012 dB/°C, the total power coupled into the fiber at -54°C will be 190 μW, at +65°C, 137 μW. Allowing 1 dB degradation to account for temporal effects, these levels are 151 μW and 109 μW respectively.

LINK BUDGET

The information developed in the preceding sections (LED-PIN link) is compiled and presented in tabular form in table 1, and graphically in figure 4. Note that even though worst case conditions have been assumed throughout, the minimum link margin is 4.9 dB.

	PRENUCLEAR EVENT		POSTNUCLEAR EVENT	
	-54°C	+65°C	-54°C	+65°C
Power coupled from source	-8.2 dBm (151 μW)	-9.6 dBm (109 μW)	-8.2 dBm (151 μW)	-9.6 dBm (109 μW)
Cable loss (300 m)	-5.1 dB	-3.0 dB	-23.1 dB	-21 dB
Connector loss (4 each)	-10 dB	-10 dB	-10 dB	-10 dB
Power coupled to detector	-23.3 dBm (4.7 μW)	-22.6 dBm (5.5 μW)	-41.3 dBm (74 nW)	-40.6 dBm (87 nW)
Power required at detector (BER $\leq 10^{-9}$)	-46.2 dBm (24 nW)	-46.2 dBm (24 nW)	-46.2 dBm (24 nW)	-46.2 dBm (24 nW)
Link margin	22.9 dB	23.6 dB	4.9 dB	5.6 dB

Table 1. Ground launched cruise missile fiber optic data link link budget.

BUILT-IN TEST

Built-in test (BIT) as cited in the STS RFP, requires a 99% assurance that mission critical faults or unsafe conditions be detected with a false alarm rate of less than 2%. The following approach outlines a logical sequence of tests which addresses the above requirement. The central design philosophy revolves about the following ground rules:

1. The LCC STS BIT function will provide to the LCC data processing system (DPS), the status of all LCC and TEL fiber optic transceivers (FOXs), as well as the LCC-TEL fiber optic cable.

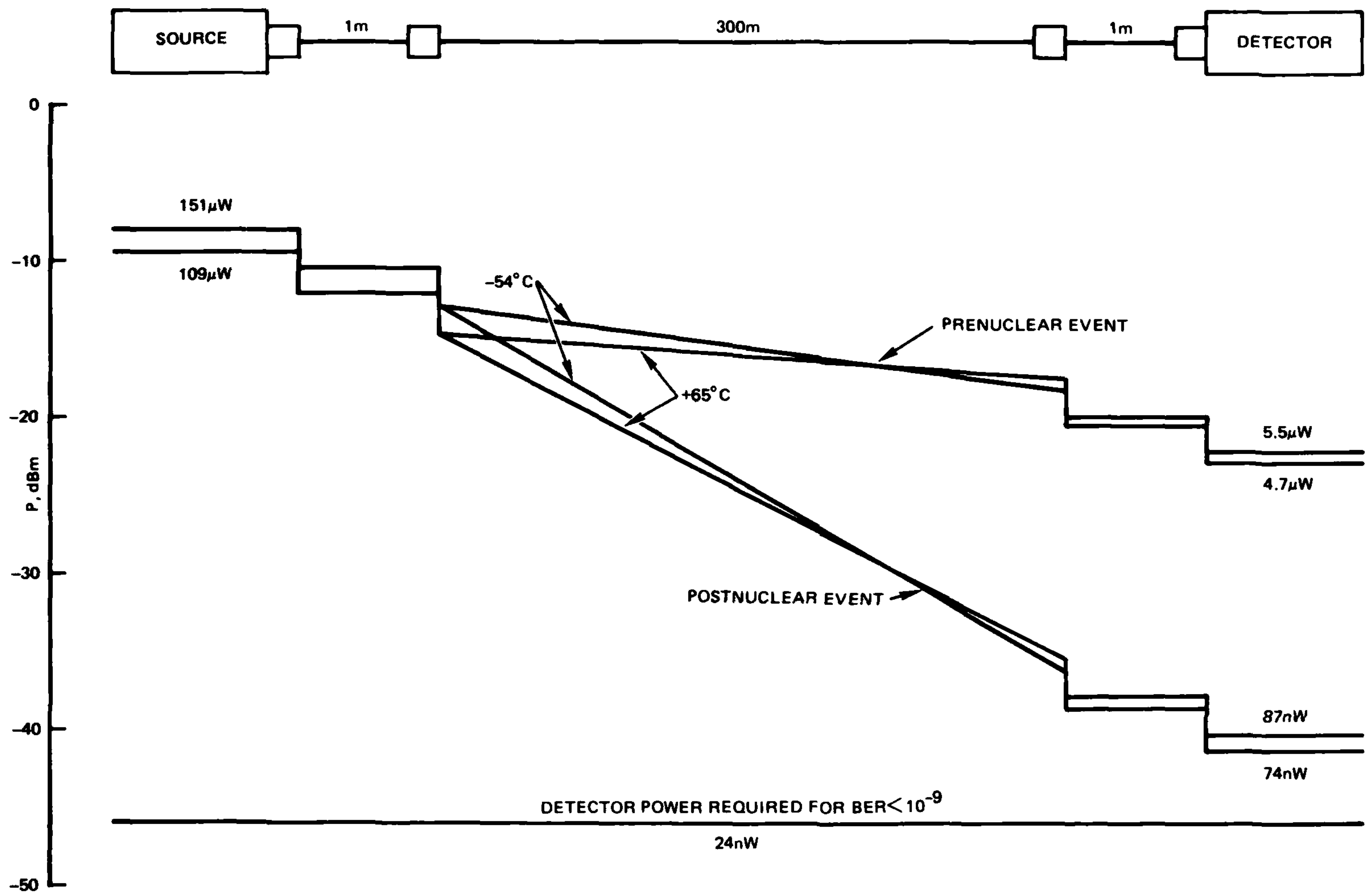

Figure 4. Ground launched cruise missile fiber optic data link link budget.

2. After BIT, on-line monitors will provide real-time GO/NO-GO status.

3. BIT provides sufficient information to isolate any fault to the line replaceable unit (FOX).

Each FOX in both LCC and TEL is monitored by couplers at both optical ports (see figure 5). Two BIT FOXs are used to interrogate and measure the response of the LCC FOXs. The BIT controller, upon command of internal test, provides a test message to the LCC FO receivers via the BIT FOX. The controller sequentially samples each LCC FOX and makes a message comparison. Two such tests are made – one at normal optical input power (at LCC FOX), followed by a second to simulate the cable losses of a nuclear event (shown as HI and LO in figure 5). The BIT controller next sequentially interrogates all LCC optical transmitters and performs a message comparison to the output of the BIT FOX. The LCC data processing system (DPS) indicates the result of each test to the system operator. Likewise, the TEL operator independently performs the same tests. However, at this point the LCC-TEL FO cable has not been connected. The BIT internal (INT) test could be performed during the deployment of the fiber optic cable, with the test period controlled by the length and repetition of the message. LCC testing would be automatically terminated by software, with manual override provided as redundancy. The TEL at completion of BIT INT sends a status report over all three return lines. A manual override is likewise provided.

The fiber optic cable is next attached to the TEL and BIT external (EXT) is performed. The BIT EXT provides TEL FOX status to the LCC, fiber optic cable condition, and line monitoring.

Upon reception and storage of the TEL status report, the LCC sends a command over all three lines requesting the TEL to configure for a FOX end-around test. The TEL BIT controller responds by connecting each FOX receiver to its transmitter. The LCC BIT controller sequentially tests the three duplex links via the message described earlier. The FOX receivers could be designed to access the SNR, thereby determining if sufficient margin exists to remain operable after a nuclear event. The LCC DPS would again show discrete responses to the tests.

Upon completion of external BIT control, both LCC and TEL system control would return to the operator. During real time, zero crossing detectors could be used to monitor receiver outputs. A GO/NO-GO operational condition for each TEL receiver could be multiplexed and transmitted to the LCC via the unused channel. Thus, all receivers could be continuously monitored by the LCC computer.

While the described testing in theory provides unit level fault information to the LCC operator, implementing a hardware design consistent with the stated 99% error detection probability imposes severe tolerance constraints on the BIT components. As an example, simulated nuclear event testing (low level) on the FOX receivers implies injecting a signal approximately 12 dB optical above the noise floor. Therefore, the combined tolerance of the BIT transmitter output power, star couplers, and connectors, could be no more than 1 to 2 dB over temperature. Likewise, the FOX receiver SNR measurements made during the LCC-TEL end-around test would be subject to the same accuracy. The stated 99% probability does not seem viable without complicated and expensive measurement techniques. Unit level testing itself imposes the necessity of FOX output controllers and software management of BIT either in a dedicated processor or as a program resident within the system computer. Using standard components, BIT testing could provide a gross confidence test, but certainly no guarantees.

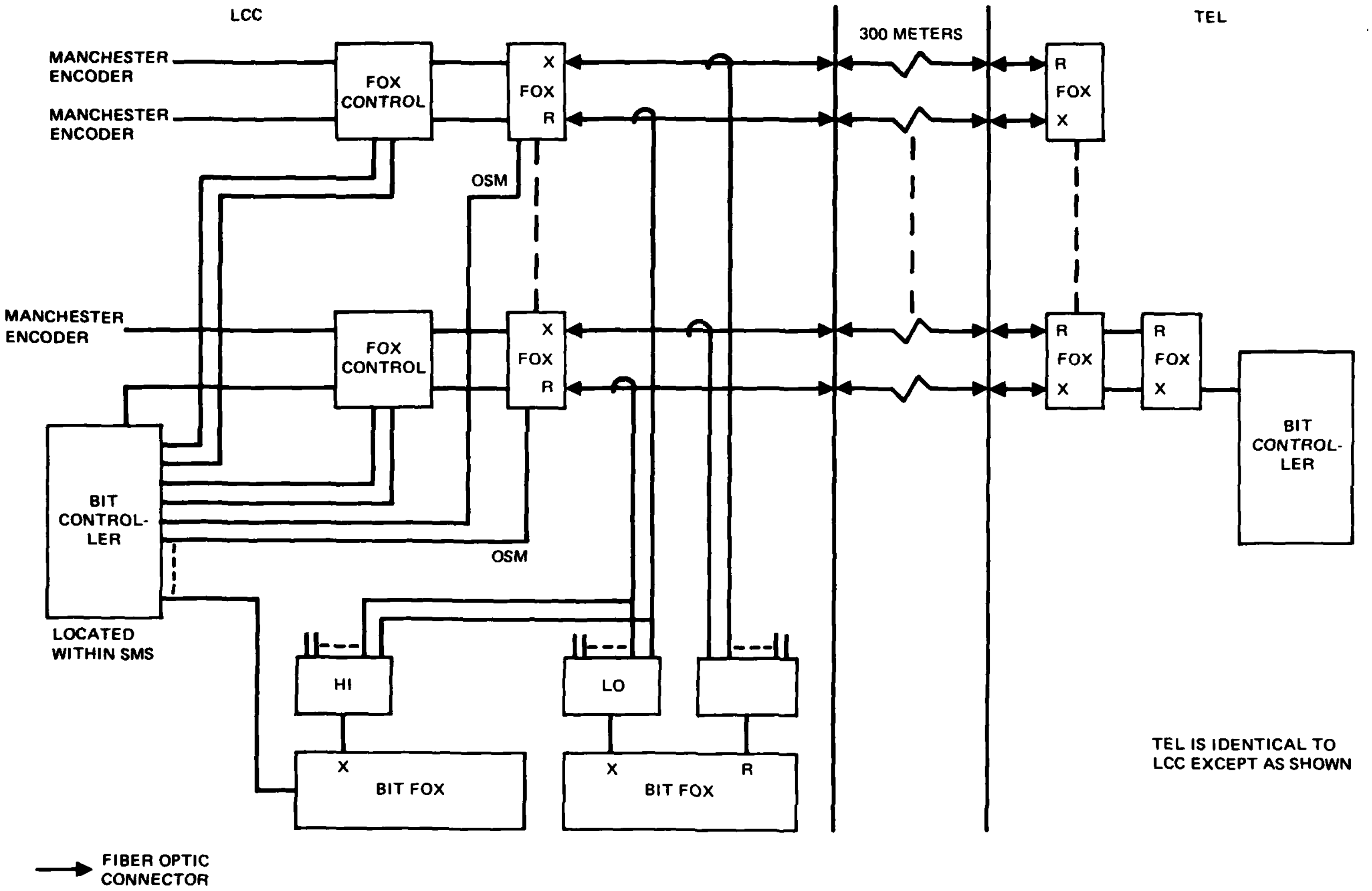

Figure 5. BIT functional block diagram.

In whatever fashion BIT is implemented, one issue should without question be addressed. Because the FOX receiver possesses a wide dynamic range, a high loss LCC-TEL FO cable could be used without apparent detrimental effect to system performance, but could cause a catastrophic failure if exposed to a nuclear event. After LCC and TEL are interconnected, the cable must in some fashion be tested.

RADIATION HARDENING*

The environment created by a nuclear burst poses three distinct threats to exposed electronic systems. The first threat the GLCM FODL would encounter is an electromagnetic pulse (EMP), followed closely by transient nuclear radiation (gamma rays and neutron bombardment), and finally by thermal radiation. Each of these threats will be examined in turn, and methods proposed to counteract their effects.

ELECTROMAGNETIC PULSE (EMP)

A high altitude nuclear burst (above 40 km) produces gamma rays that move radially outward from the burst. These rays are absorbed in the earth's atmosphere via the mechanism of collision with air molecules. These collisions, in turn, create free electrons (Compton electrons) which are deflected along the geomagnetic lines of force (transverse to the direction of radiation). This deflection creates intense electric fields containing significant energy throughout the spectrum from 10 kHz to 100 MHz, which propagate toward the earth.

A low altitude nuclear burst creates an EMP via the same Compton electron mechanism as the high altitude burst. The difference here, however, is that an intense electric field is produced by charge separation between the free electrons and the heavier positive ions (created by the electron displacement). These electric fields propagate radially from the burst, and contain most of their energy in the spectrum below 1 MHz.

NEUTRONS AND GAMMA RAYS

The first gamma rays (prompt gamma) generated by a nuclear burst typically represent one percent of the burst's yield. They are generated by fission, fusion, neutron capture, inelastic scattering, and radioactive decay, and propagated into space at the speed of light. The prompt gamma generates an ionizing pulse, typically 10 ns wide, which contains a very high level of energy. A secondary gamma effect (delayed gamma) is the result of neutron interaction with the atmosphere. This gamma environment is much less intense than prompt gamma, but of a much longer duration (10 to 100 μs). Finally, there is one more measure of the transient radiation environment. This measure is the total ionizing dose which is a composite of accumulated gamma from all sources.

The neutron environment is the result of fission and fusion reactions in the burst, and represents approximately one percent of the burst's yield. Since the neutron particles are chargeless, the neutron fluence is not effectively attenuated by the atmosphere and should be assumed incident upon the entire GLCM WCS.

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*See Marion A. Rose, Nuclear Hardening of Weapon Systems, Defense Electronics, September, October, November 1979.

THERMAL RADIATION

As a result of the enormous amount of energy released in a relatively small space, absorption by the air of x-rays created by the fission and/or fusion, and the dissipation of kinetic energy associated with the blast debris, a fireball is created. About thirty percent of the total blast energy manifests itself in this thermal energy, radiating in all directions. The duration of the thermal pulse may be from less than a second to tens of seconds, depending on the yield of the device.

NUCLEAR EFFECTS

The EMP affects electronics by inducing undesirable transient currents on interconnective cables, antennas, box surfaces, internal leads, shields, and in general, on any metallic surface that the pulse penetrates to. Basically there are three modes of EMP penetration; diffusion of field energy through metallic exterior surfaces, penetration via exterior cables or antennas (either intentional or unintentional), or through apertures which include every sort of hole in the metal exterior of the system. These EMP induced currents can cause problems ranging in magnitude from temporary upset to component destruction.

Neutrons penetrate the system totally, affecting active electronic components by causing permanent defects within their semiconductor crystalline structures. This causes permanent degradation and/or destruction of these components, with a resultant deterioration in system performance.

The thermal pulse can induce significant temperature rises in system electronic components. This can cause deleterious effects ranging from temporary system degradation to total failure.

EMP HARDENING

Designing against EMP is basically the same as designing against radio frequency interference (RFI), and the same general rules apply.

1. If possible, enclose all system electronics in solid shells of moderately thick aluminum.

2. Ensure clean metal-to-metal mating surfaces in the mechanical assembly of all enclosures.

3. Ensure good contact between mating surfaces by using soft conductive gasketing and a continuous bond, or set screws or rivets at close intervals.

4. To reduce EMP field penetration, cover all unavoidable openings in the enclosures (air conditioning, etc) with honeycomb or wire mesh screen.

5. Shield all metal cables, with complete shield continuity maintained at the connector backshells.

6. Filter and protect from transient spikes (with zener diodes, spark gaps, tranzorbs, etc) all penetrating conductors.

7. Use equipotential grounding for localized areas, and ensure that topological grounding conductors never penetrate enclosure surfaces.

GAMMA HARDENING

The basic rules for designing against gamma rays follow:

1. Enclosures with high lead contents make effective gamma shields.

2. Use current limiting series resistors in all power supply leads feeding active devices.

3. Use only dielectric isolated integrated circuits.

4. Protect all active devices from potential inductive kicks.

NEUTRON HARDENING

The basic rules for designing against neutrons follow:

1. Hydrogenous materials such as water, polyethylene or paraffin (with boron 10 added) should be the primary ingredient of a neutron shield.

2. Use transistors with $f_T > 50$ MHz, if possible.

3. Bias all transistors to operate near the peak of their h_{fe} vs collector current curves.

4. Use only high speed operational amplifiers.

5. Derate the fanout of digital devices to allow for degradation.

THERMAL HARDENING

In designing the GLCM FODL, the following thermal hardening rules should be followed:

1. Make enclosure surfaces of light colored, high temperature resistant materials.

2. Use thermal insulating materials or otherwise eliminate direct thermal conduction between exposed surfaces and heat sensitive electronic components.

In addition to adhering as closely as possible to the hardening principles outlined above, the GLCM FODL design will incorporate a radiation circumvention scheme. A fast-acting radiation-sensitive switch will be used to power down the FODL for a preset period, and then to automatically apply power once the major nuclear threat has passed. This scheme, used in conjunction with good radiation hardening practices, will provide the FODL with a maximum of protection against any nuclear threat.

CONCLUSIONS

1. The electrooptic and electronic portions of the GLCM FODL are well within current state-of-the-art design practices.

2. Current radiation hardening practices for electronic systems are adequate to meet the GLCM FODL requirements.

3. Fully tested and qualified cables and connectors do not presently exist; however, work is ongoing in both areas. Six months should see technically adequate cables and connectors available.

RECOMMENDATIONS

1. Closely monitor the progress of cable and connector development and testing on a worldwide basis.

2. Procure, for testing specifically oriented to GLCM requirements, candidate cables and connectors.